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THE NASA RESEARCH PROGRAM ON PROPULSION FOR SUPERSONIC CRUISE AIRCRAFT

by Richard J. Weber
Lewis Research Center
Cleveland, Ohio 44135

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by Richard J. Weber

National Aeronautics and Space Administration

Lewis Research Center

Cleveland, Ohio

ABSTRACT

Since 1972 NASA has pursued a program aimed at advancing the technology and establishing a data base appropriate for the possible future development of supersonic cruise aircraft. This paper briefly reviews the objectives and status of the propulsion portion of the program. Building upon a continuing series of propulsion system studies, research activities are underway in noise and pollution reduction, inlet stability, and materials.

INTRODUCTION

In 1963 the U.S. initiated a program aimed at the development and production of a commercial supersonic transport (SST). In 1971 the project was abandoned as a result of concerns about technical readiness, economic feasibility, federal financing, and environmental impact. In 1972 NASA started what is now called the Supersonic Cruise Airplane Research (SCAR) program. In contrast to the earlier SST project, the SCAR work is not aimed toward a production airplane, but rather, it is intended to establish a data base of advanced technology to be available for the design of future aircraft if and when the nation determines it is desirable to build them. The various elements of the program are relevent in varying degrees to both potential civil and military applications.

The total SCAR program has been funded at an annual rate of about 9 million dollars per year. It involves work in propulsion, aerodynamics, structures, and stability and control. However, this paper is limited to a survey of the SCAR propulsion activities. In this discussion, it should be recognized that there are many other projects within the general NASA research program that are applicable to both subsonic and supersonic flight. The intent of the SCAR program is to supplement the general activities with additional work that is focussed on those unique problems of supersonic aircraft that would otherwise not receive adequate attention.

RESEARCH ELEMENTS

The philosophy of the SCAR program has been to perform the great majority of the work through contracts with industry. Table I lists the propulsion contracts that have been let since the program's inception. The work can be divided into the general categories of:

Engine studies

Noise reduction

Pollution reduction

Propulsion dynamics

Unique components

The work in each of these categories will be briefly described in the following sections. As an indication of the relative effort expended in each category, table II shows how the propulsion budget has been distributed in each fiscal year. The total propulsion expenditures represent about one-quarter of the available SCAR funds.

PROPULSION SYSTEM STUDIES - Considerable work had been invested in propulsion during the original SST project, culminating with the building and testing of a preprototype engine - the GE/4, an afterburning turbojet. Nevertheless, when the SCAR program was begun, it was decided to start anew with a very broad study of all the plausible competing propulsion concepts. Starting from this broad base of parametric systems, it was planned to progressively move through a series of later studies, each time focussing in greater detail on a smaller number of promising candidates. This approach is represented by the triangle of figure 1. The results of the studies were to serve several purposes:

- to determine the favored propulsion concept (s)
- to identify the associated technology needs in order to guide

the supporting research activities that are described in the later sections of this paper

- to generate engine performance data to be used in overall airplane studies by airframe contractors in other parts of the SCAR program
- ultimately, to define an experimental engine program, if the selected concept were sufficiently unusual and if funds were available

There were several reasons for starting with such a broad-based study program:

- The entire SCAR program is a long-term one, having no specific target date, thus allowing time for a new, open-minded analysis that could incorporate advances in technology.
- Environmental considerations are recognized to a greater degree than in the SST project, with a correspondingly greater impact on engine design.
- New engine concepts have been proposed which require extensive study before their true merits can be established.

The program that was set up has involved major contracts with the General Electric Company and Pratt and Whitney Aircraft Company. These contracts have addressed the conventional engine concepts (dry turbojet, afterburning turbojet, duct-burning turbofan, afterburning turbofan) plus a number of unconventional, variable-cycle engines (VCE). Other types of VCE's have also been studied by Advanced Technology Laboratories, Rockwell International, and the Boeing Company.

It was presumed in these studies that an advanced commercial supersonic transport would have to meet the same environmental regulations as new subsonic transports. In the case of noise, the studies sought to determine the ability of each engine type to satisfy the present FAR-36 limits and also to find the penalties involved in meeting more stringent limits, which might be in force at the time a future airplane is placed into service (perhaps 10-20 years from now).

The widely varying flight conditions faced by a supersonic transport, aggravated by the noise constraint, make it difficult to design a light-weight, efficient, conventional engine. For example, good takeoff thrust, low jet noise, and efficient subsonic operation are best provided by a high-bypass-ratio turbofan. On the other hand, best supersonic cruising is obtained with a low-bypass-ratio turbofan or a turbojet. The variable-cycle engine tries to satisfy both of these requirements through internal changes of airflows and jet velocities. Many techniques have been proposed for accomplishing this; the real problem is how to do it without incurring excessive weight and drag penalties.

Figure 2 shows that definite progress has been made by means of cycle optimization and technology advances from what was available in the original SST program. The improvements are primarily reflected in the ability to achieve lower noise levels - to the point where the noise footprint area approaches that of a modern wide-body subsonic jet transport. However, continued engine improvements are still desired to better the airplane performance and economics.

NOISE REDUCTION - Concern about the noise generated by the powerful supersonic engines has been found to have a major impact on engine design and resulting airplane performance. Unlike subsonic engines, the supersonic engines tend to have very high exhaust velocities, and so their major problem is excessive jet noise. The preceding section mentioned how attempts were being made to alleviate this problem through engine design. This section describes the SCAR technology programs that seek to better understand the character of jet noise and hopefully find ways to reduce its effect. (This work supplements other major national research on engine noise, e.g. DOT/FAA contracts with industry on suppressor technology.)

One of the results of the propulsion system studies was to point out the potential of dual-stream engines, in the form of a turbofan or of a VCE that behaved like a turbofan at low speeds. Little work has been done in the past on the jet noise of such engines, so a program has been started in the area of coannular jets. The objective of the work is to study the acoustic and aerodynamic performance of coannular nozzles, both with and without suppressors and ejectors. A wide range of exhaust pressures and temperatures in both the primary and duct streams are being tested in static facilities. The potential of acoustical treatment is also being investigated. This work was begun in August 1973, through contracts to P&W and GE, and will be completed in 1975.

Figure 3 shows a typical suppressed nozzle of the type being tested. The model is about 13 cm (5 inches) in diameter, which is about 1/10 scale. Some of the acoustic test results are shown in figure 4, in which the data have been adjusted to full scale and to the standard FAR-36 sideline measuring distance. Perhaps the most interesting fact to observe is that the coannular nozzle possesses up to 8dB of inherent noise suppression in the region where the duct velocity is higher than the core velocity. A similar amount of additional suppression has been measured for the combination of a multitube suppressor and an ejector with acoustical lining. The total of 15dB suppression was obtained with about 7 percent thrust loss.

The preceding results have been obtained under static conditions. However, it has been observed in the past that in-flight suppressor performance tends to be worse than static. Figure 4 illustrates how important it is to properly account for the flight effects. Until fairly recently it was common to adjust static measurements of noise to flight conditions through a "relative velocity" correction specified by a standard SAE document. Furthermore, it was usually assumed that a noise suppressor is as effective in flight as it is statically. However, as shown in the figure, recent flight data indicate that both of these approaches are overly optimistic. Hence, it is planned in future work with coannular nozzles to extend the tests to simulations of the flight environment.

In the meantime, fundamental studies have been initiated by both Boeing and Lockheed. These studies will investigate the theoretical and practical problems associated with acoustical propagation from a moving source to a stationary observer, plus jet-noise source alteration due to motion of the surrounding air, and techniques to verify these effects.

An additional basic study that is planned to start soon will obtain experimental data on atmospheric absorption of noise as a function of temperature and humidity for frequencies up to 100,000 hertz. The high frequency information is necessary to interpret model scale data, especially on suppressed configurations with very small elements.

POLLUTION REDUCTION - Growing concern has been evidenced in recent years about the problem of pollution of the atmosphere. Although aircraft are relatively small contributors to this problem, they are felt to be significant polluters in the vicinity of airports. Accordingly the Environmental Protection Agency has established goals for the reduction of carbon monoxide, unburned hydrocarbons, and nitrogen oxides emitted by subsonic transports during the takeoff and landing process. Supersonic aircraft add a new dimension to the problem. They will cruise at altitudes well into the stratosphere (20km), which has aroused fears of possible adverse climatic effects. One concern is that the formation of SO_2 may affect atmospheric opacity and thus change surface temperatures. Removal of sulphur during the fuel refining process can eliminate this problem. The principal remaining worry is that nitrogen-oxide emissions will cause a gradual reduction in ozone concentration; this would permit more ultra-violet radiation to reach the surface, with possible adverse effects on plants and the incidence of skin cancer. The recent conclusions of the Climatic Impact Assessment Program of the Department of Transportation show that this problem is not as great as some had originally suggested. Nevertheless, there is an apparent need to reduce, over the long run, nitrogen oxide emissions below the levels generated by current conventional combustors. Anticipating this need, even though there are no applicable EPA regulations for high-altitude emissions, NASA has initiated a program aimed at achieving substantial NO_x reductions.

The principal technique that is being explored is to reduce flame temperature by fuel-lean combustion, combined with premixing/prevaporizing to achieve a uniform mixture. An indication of the potential of this approach is shown in figure 6. Very low values of emission index (grams of NO_2 produced per kg of fuel burned) are seen to be achievable without penalty to combustion efficiency. These index values are in contrast to the 15-20 g/kg typical of current combustors. The data of figure 6 were obtained in idealized combustion experiments; these low values are probably not achievable in actual engines.

Figure 7 summarizes progress to date, using various combustor techniques ranging from experimental combustors to idealized conceptual tests. The results of the premix, lean combustion, and catalytic approaches are extremely promising, but several more years of laboratory work followed by combustor development and demonstration will be needed before it is known what value is realistically achievable.

The preceding discussion has been in terms of primary combustors. The turbofans and variable-cycle concepts now being considered usually incorporate either afterburners or duct burners, which may be used during both takeoff and cruise. The typically low pressures and high velocities in an augmentor tend to make high efficiency and low emissions difficult to achieve. It is hoped to start an extensive research program in this area in the near future.

PROPULSION DYNAMICS - The performance of a supersonic airplane is quite sensitive to the performance of the inlet diffuser, which must capture the streamtube of rapidly-moving air, slow it to low velocity, and efficiently convert its kinetic energy to high pressure before entering the engine. In the mixed-compression type of inlet that is of present interest for a supersonic transport, maximum performance is obtained when the air is decelerated to subsonic velocity through a terminal shock that is located at the throat (i.e. minimum-flow-area point) within the inlet. If the shock is allowed to move downstream, the pressure recovery of the inlet suffers and there is high distortion of the airflow. However, with the shock near the throat, small changes in engine flow or inlet capture flow can create an inlet unstart. An unstart is when the shock moves upstream of the throat, which is an unstable location, and then rapidly pops out of the inlet entirely, which results in a large thrust loss, a tendency for the airplane to yaw and roll, and passenger discomfort. Typical causes of such unstarts are: engine throttle changes, augmentor light-up, atmospheric turbulence or temperature variation, shock waves from other aircraft.

A new type of inlet stabilization device to minimize this occurrence of unstart is presently being investigated that has faster response and lower losses than previous techniques. The new approach, like many previous ones, operates on the principle of bleeding air out of the inlet whenever the shock moves too far upstream. Excess airflow bypasses the engine until the inlet by-pass doors can open, returning the shock to its desired throat position. The new device mechanizes this principle by means of a series of poppet valves spaced about the circumference of the inlet, as sketched in figure 8. A photograph of the valve parts is shown in figure 9.

A feasibility study contracted to Lockheed Aircraft Company resulted in a suitable valve design. Under a later contract they designed and fabricated a complete valve system for the inlet of the YF-12 airplane, the only U.S. airplane that is capable of long-range supersonic flight. Prototype valves were successfully tested in a special dynamic facility at NASA/Lewis. An actual YF-12 inlet, modified to contain 50 of the valves, is now undergoing tests in the Lewis 10 x 10-Foot Supersonic Wind Tunnel. Depending on the results, it is possible that there will be a flight test on the YF-12 airplane.

UNIQUE COMPONENTS - The preceding sections have described research related to exhaust nozzles, combustors, and inlets that is covered by the noise, pollution, and dynamics programs. It was felt that the propulsion systems studies would identify other supersonic engine components that deserved attention. These components are covered under the final catch-all category of "Unique Components." The primary subject that has so far been addressed in this category is the general one of materials. Improved materials are recognized to be beneficial in any type of engine; however, the unique design and operating conditions of a supersonic engine has led to work in two particular areas.

Fan blades - Some of the most promising supersonic propulsion systems are turbofans or variable cycles that contain fans. These fans would use thin, sharp-edged blades similar to, although larger than, the one pictured in figure 10. Such a blade is normally made of solid titanium. Much effort has been invested in the past toward the use of lighter-weight composite materials instead of metal. The usual composites are not applicable to the hotter environment of a supersonic engine. The current program is aimed at the development of boron-aluminum blades, which can tolerate the higher temperatures. Successful development of such blades would eliminate the part-span shrouds, reduce blade weight by 35 percent, and permit additional reductions of disk and containment weight. For a typical supersonic transport these improvements would result in a decrease in takeoff gross weight of 3.5 percent.

The major obstacle facing the use of B/Al composites has been poor impact resistance. Prior studies have demonstrated good static properties, but foreign object damage such as from bird strikes has caused catastrophic failure. The approaches selected in the present program to improve B/Al impact strength are: a more ductile aluminum alloy matrix, promoting energy absorption through plastic deformation; larger diameter boron filaments, increasing the spacing between filaments to permit the matrix to deform in a ductile manner; fabrication processes, selected to reduce reaction at the fiber-matrix interface to increase filament strain to failure; and filament ply lay-up that is optimized for the more ductile behavior.

The potential of these approaches in terms of Notched Charpy pendulum impact strength is pictured in figure 11. The original B-Al technology provided Charpy values of 3-8 foot-pounds and very brittle failures. Use of a slightly more ductile matrix, 5052 Al, raised this value to 13 ft-lb (upper left). Use of the still more ductile 1100 Al matrix raised the strength to 47 ft-lb, with a significant amount of plastic deformation present at failure (upper right). Substituting the larger 8-mil-diameter filament raised the strength to 68 ft-lb, with an even greater amount of plastic behavior.

These results offer hope for the successful completion of the current B-Al program, which includes obtaining design data, fabricating and testing blades in whirling arm impact tests, and demonstration of performance gains in ground engine tests.

Exhaust system components - A supersonic propulsion system has many more complex and heavy parts exposed to hot exhaust gases than does a subsonic engine (e.g. variable-geometry convergent-divergent exhaust nozzle, noise suppressor, and augmentor). Consequently, the benefit of using lighter-weight materials is marked. The objective of the present program is to investigate and demonstrate the capabilities of SiC-fiber-reinforced superalloy sheet for reducing the weight of supersonic propulsion systems. The nozzle/suppressor/reverser portion of each engine typically weighs about 3000 pounds. Because of its lower density, the composite sheet could reduce this weight by 30 percent. This in turn would reduce airplane gross weight by 5 percent. This does not account for the additional weight savings from the following improvements in projected mechanical properties, measured at 1250K ($1800^{\circ}F$): four times greater strength, two times greater modulus, and five times greater 1000-hour rupture strength.

To verify this potential, an experimental program is underway that will screen candidate matrixes, develop fabrication techniques, and test panels and actual component shapes.

CONCLUDING REMARKS

A long-term research program is being conducted by NASA to establish a data base to be available for possible development of future supersonic aircraft. The effort does not compare in magnitude or cost to the activities that pertained to the early SST development project. However, considerable progress has since been made in the various propulsion-related fields. It seems clear that the advances being made will be of great value to the design of tomorrow's supersonic airplanes.

Table I. - SCAR Propulsion Contracts (through January 1975)

Contractor	Title	Start
	Engine Studies	
Advanced Technology Labs. (NAS3-17559)	Study of an Unconventional Variable Cycle with a Supersonic Inflow Fan	Sept. 1972
Pratt & Whitney Aircraft (NAS3-16948)	Advanced Supersonic Propulsion Technology Studies	Sept. 1972
	Extension I	Jan. 1974
	Extension II	April 1975
General Electric Company (NAS3-16950)	Advanced Supersonic Propulsion Technology Studies	Oct. 1972
	Extension I	Jan. 1974
	Extension II	April 1975
Pan American World Airways (NAS3-17216)	Airline Appraisal of AST Engines	Jan. 1973
Rockwell International Corp. (NAS1-12245)	Study of a Multimode Integrated Propulsion System in an Advanced Supersonic Transport	April 1973
	Noise Reduction	
Pratt & Whitney Aircraft (NAS3-17866)	Acoustic Tests of Duct-Burning Turbofan Jet Noise Simulation	Aug. 1973
General Electric Company (NAS3-18008)	Acoustic Tests of Duct-Burning Turbofan Jet Noise Simulation	Aug. 1973
The Boeing Company (NAS3-18539)	Effects of Motion on Jet Exhaust Noise from Aircraft	July 1974
Lockheed (NAS3-18540)	Effects of Motion on Jet Exhaust Noise from Aircraft	July 1974

Table I. - SCAR Propulsion Contracts (through January 1975) continued

Contractor	Title	Start
	Pollution Reduction	
Pratt & Whitney Aircraft (NAS3-16829)	Experimental Clean Combustor Program, Phase I (AST Addendum)	June 1973
General Electric Company (NAS3-16830)	Experimental Clean Combustor Program, Phase I (AST Addendum)	Aug. 1973
Solar Div. - Int'l. Harvester (NAS3-18023)	Experimental Study of Advanced Combustor Concepts to Reduce Formation of Oxides of Nitrogen in Gas Turbine Engines for High-Altitude Aircraft	March 1974
Advanced Technology Labs. (NAS3-18563)	Development of Concept for Low NO_x - Premixed, Prevaporizing Combustor	Oct. 1974
	Propulsion Dynamics	
Lockheed	Feasibility Study of Inlet Shock Stability System of YF-12	April 1972
Lockheed	YF-12 Inlet Shock Stability System for Wind Tunnel Tests	May 1973
	Unique Components	
General Electric Company (NAS3-18910)	Boron-Aluminum Fan Blades for AST Engine	June 1974
Westinghouse Electric Co.	Fabrication Process Development of SiC/Superalloy Composite Sheet for Exhaust System Components	June 1974

Table II. - SCAR Propulsion New Obligational Authority (thousands of dollars).

Fiscal year	1973	1974	1975
Engine studies	1078	1380	800
Noise reduction	307	293	745
Pollution reduction	392	249	575
Propulsion dynamics	283	213	0
Unique components	0	240	100
Total	2060	2375	2220

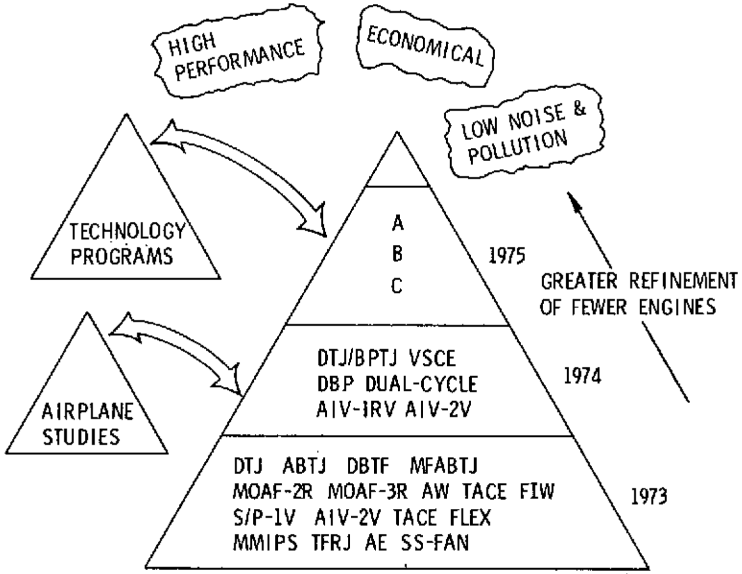

Figure 1. - Progress of propulsion system studies.

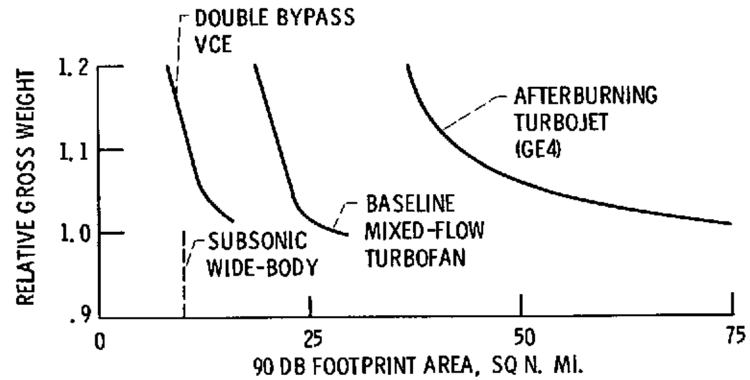

Figure 2. - Propulsion system comparison, 292 pax, 4000 n. mi. range, M_{cr} = 2.32, ref. TOGW = 762 000 lb.

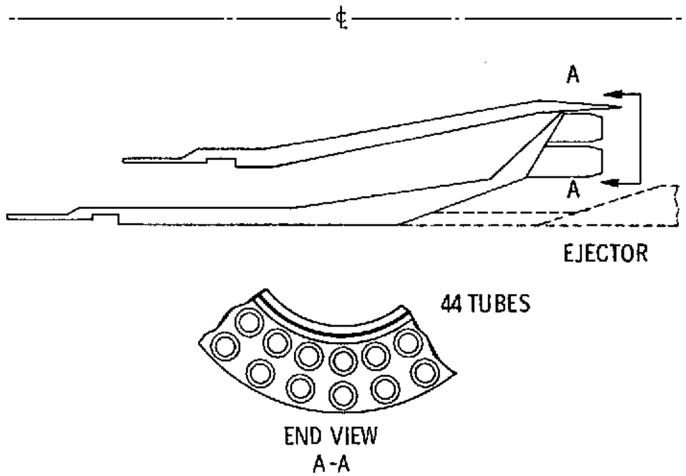

Figure 3. - Duct burning turbofan acoustic tests.

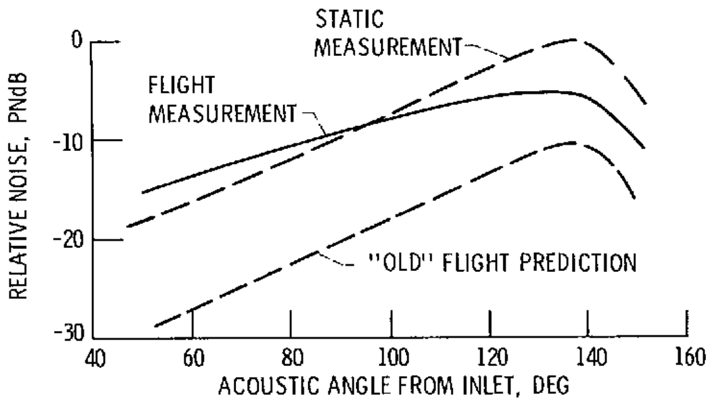

Figure 4. - Flight effects on jet noise. Suppressed conical nozzle.

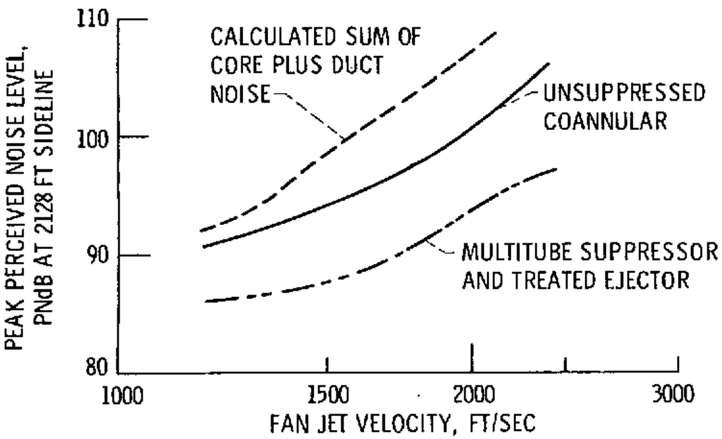

Figure 5. - Acoustic performance of coannular nozzles, core velocity, 1320 ft/sec.

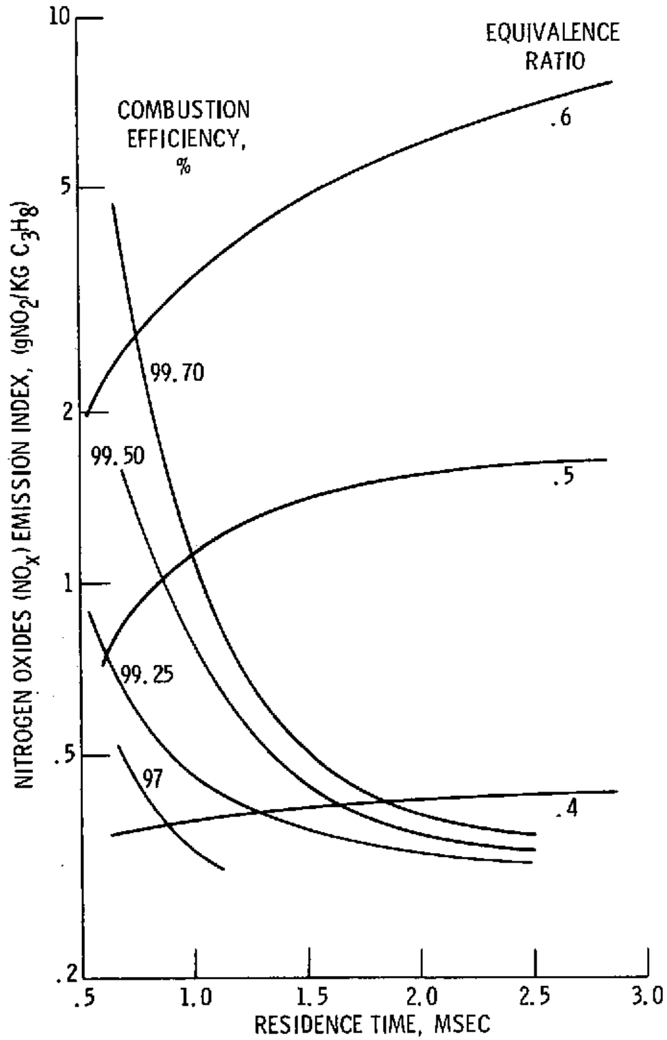

Figure 6. - Effect of residence time on nitrogen oxides emissions. Inlet mixture temperature, 800 K; inlet pressure, 5.5 atm; reference velocity, 25 and 30 m/s.

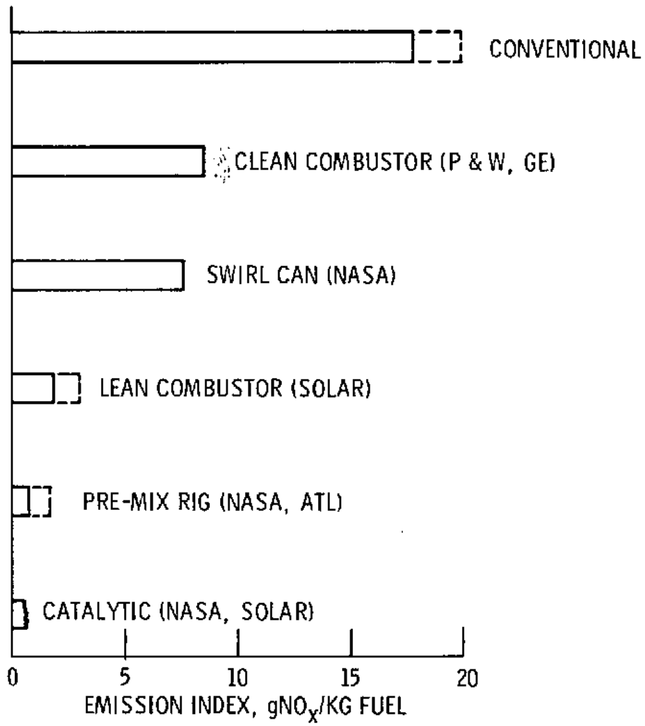

Figure 7. - Status of cruise NO_x emission experiments, $M = 2.7$, 60 000 ft.

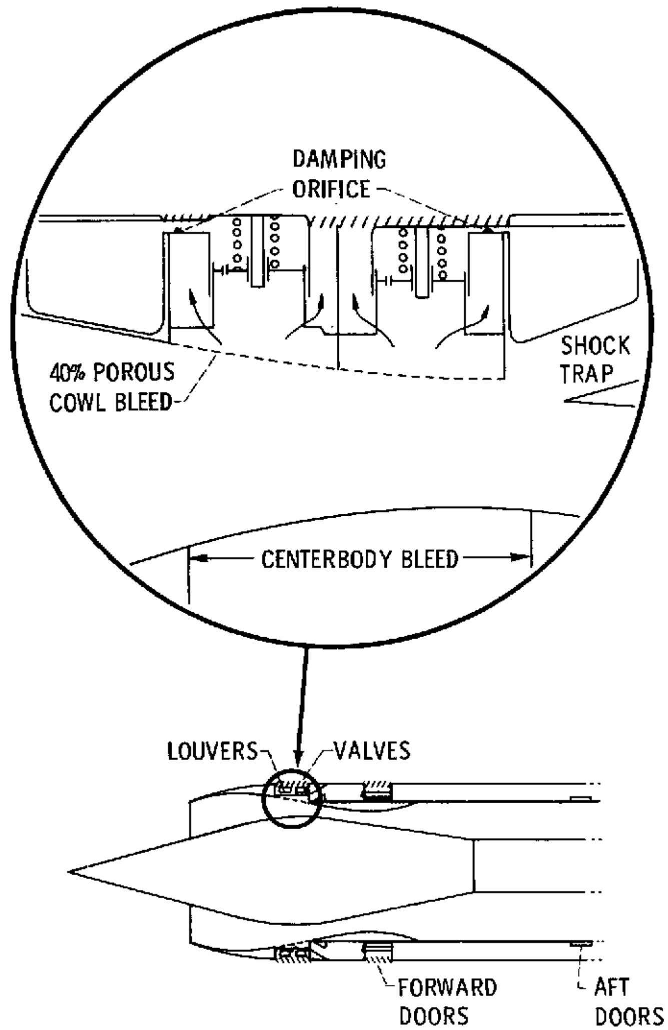

Figure 8. - Shock stability bleed system in YF-12 inlet.

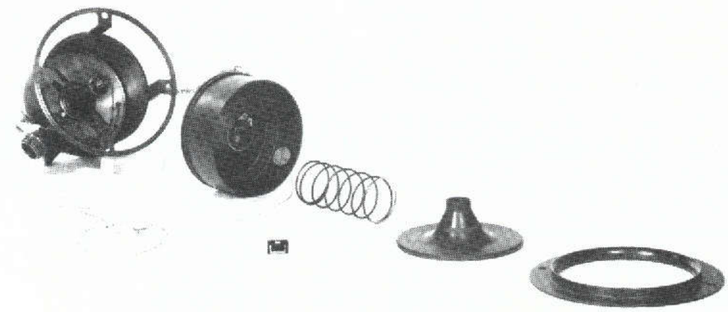

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Figure 9. - Disassembled stability system relief valve.

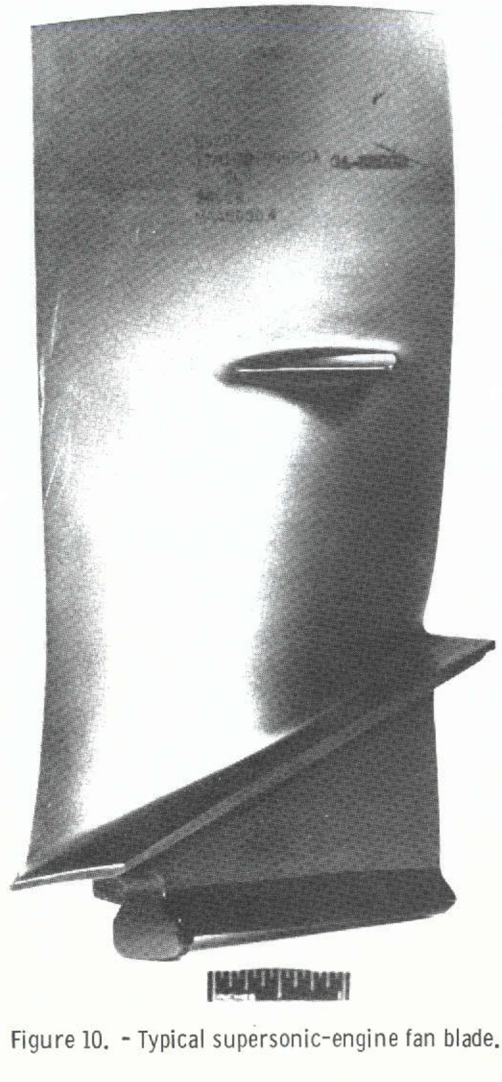
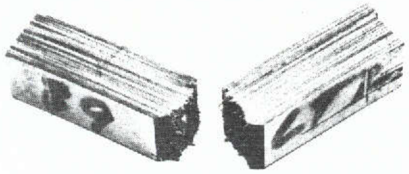
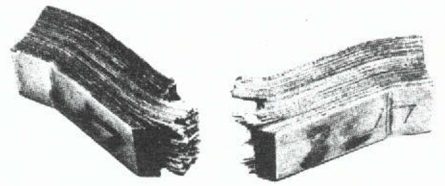


Figure 10. - Typical supersonic-engine fan blade.



13 FT-LB; 50 V/O 5.6 MIL B IN 5052



47 FT-LB; 50 V/O 5.6 MIL B IN 1100

68 FT-LB;
50 V/O 8 MIL B IN 1100

Figure 11. - Improved B/Al impact resistance.